Air Shower Measurements in Karlsruhe[1]

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Abstract. The Karlsruhe multi-detector set-ups KASCADE, KASCADE-Grande, and LOPES aim on measurements of cosmic rays in the energy range of the so called knee between 10^{14} eV and 10^{18} eV. The multidimensional analysis of the air shower data measured by KASCADE indicates a distinct knee in the energy spectra of light primary cosmic rays and an increasing dominance of heavy ones towards higher energies. This provides, together with the results of large scale anisotropy studies, implications for discriminating astrophysical models of the origin of the knee. To improve the reconstruction quality and statistics at higher energies, where the knee of the heavy primaries is expected at around 100 PeV, KASCADE has been extended by a factor 10 in area to the new experiment KASCADE-Grande. LOPES is located on site of the KASCADE-Grande experiment. It measures radio pulses from extensive air showers with the goal to establish this renewed detection technique for future large scale experiments.

1. Introduction

The all-particle energy spectrum of cosmic rays exhibits a distinctive discontinuity at few PeV, known as the knee, where the spectral index changes from -2.7 to approximately -3.1 (Fig. 1). This feature has been discovered half a century ago by German Kulikov and George Khristiansen of the Moscow State University [1] within studies of the intensity spectrum of the content of charged particles of extensive air showers, which roughly reflects the primary energy. At that energy direct measurements are hardly possible due to the low flux. Thus indirect measurements observing extensive air showers (EAS) attempt to reveal the structure of the spectrum.

The key questions of the origin of this knee are still not convincingly solved. Astrophysical scenarios like the change of the acceleration mechanisms at the cosmic ray sources (supernova remnants, pulsars, etc.) or effects of the transport mechanisms inside the Galaxy (diffusion with escape probabilities) are conceivable for the origin of the knee as well as particle physics reasons like a new kind of hadronic interaction inside the atmosphere or during the transport through the interstellar medium. An overview on the current zoo of these theoretical models were recently given in [2]. It is obvious that only detailed measurements covering the full energy range of the knee from 10^{14} eV to 10^{18} eV and analyses of the primary energy spectra for the different incoming particle types can validate or disprove some of these models. Despite EAS measurements with various different experimental set-ups in the last decades this demand could

[1] Contribution to the 80th anniversary of late Georgii Borisovich Khristiansen, the discoverer of the knee in the cosmic ray energy spectrum. He supported the start of air shower investigations in Karlsruhe with keen interest and was a great help for us at that time.

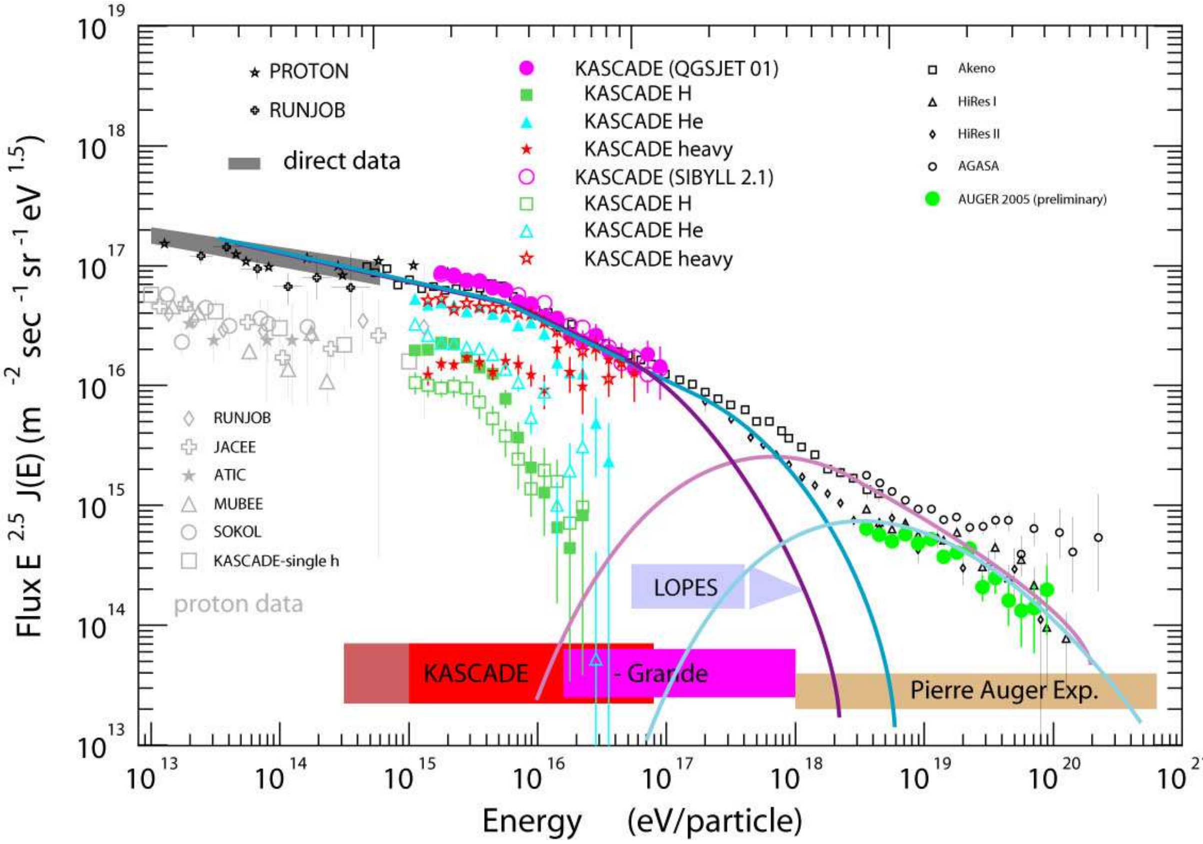

Figure 1. Primary cosmic ray flux. Results of some experiments (in particular KASCADE) for the all-particle spectrum as well as for spectra of individual mass groups, in particular for protons are displayed. Full lines show possible scenarios for the origin of a second knee in the spectrum (explanation see text chapter 4).

never accomplished, mainly due to the weak mass resolution of the measured shower observables [3].

The multi-detector system KASCADE-Grande (KArlsruhe Shower Core and Array DEtector and Grande array) [4], approaches this challenge by measuring as much as possible independent information from each single air-shower event. In 2003, the original KASCADE experiment [5], which is optimized for the energy range of 10^{14} eV to $10^{16.8}$ eV has been extended in area by a factor 10 to the new experiment KASCADE-Grande. KASCADE-Grande allows now a full coverage of the energy range around the knee, including the possible second knee at energies just below 10^{18} eV.

With its capabilities KASCADE-Grande is also the ideal testbed for the development and calibration of new air-shower detection techniques like the measurement of EAS radio emission, which is performed in the frame of the LOPES project [6]. LOPES is designed as digital radio interferometer using high bandwidths and fast data processing and profits from the reconstructed air shower observables of KASCADE-Grande.

2. The Multi-Tool Box: KASCADE, KASCADE-Grande, and LOPES

These experiments (Figs. 2, 3, 4, 5) are located at the Forschungszentrum Karlsruhe, Germany, (49.1°n, 8.4°e, 110 m a.s.l.) and measure extensive air showers in a primary energy range from 100 TeV to 1 EeV. Their combination provides multi-parameter measurements on a large number of observables of the shower components: Electrons, muons at 4 energy thresholds, hadrons, and the radio emission. The main detector components are the KASCADE array, the Grande array, and the LOPES antenna array.

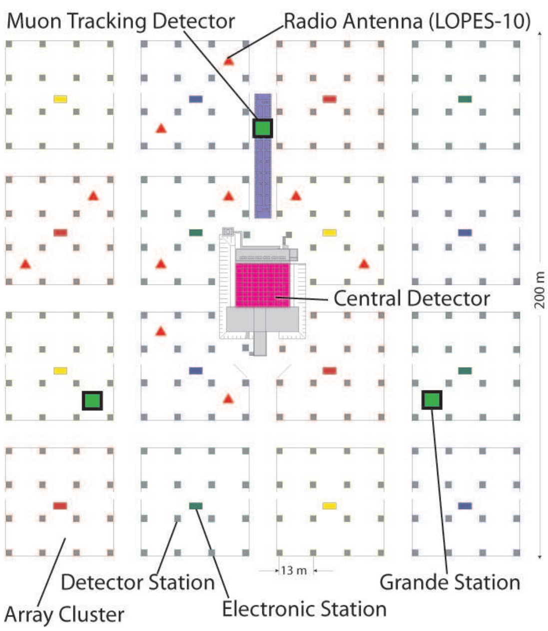

Figure 2. Sketch of the KASCADE experiment: field array, muon tracking and central detector. The outer 12 clusters of the array consists of μ- and e/γ-detectors, the inner 4 clusters of e/γ-detectors, only. The locations of 10 radio antennas of LOPES 10 are also displayed, as well as three stations of the Grande array.

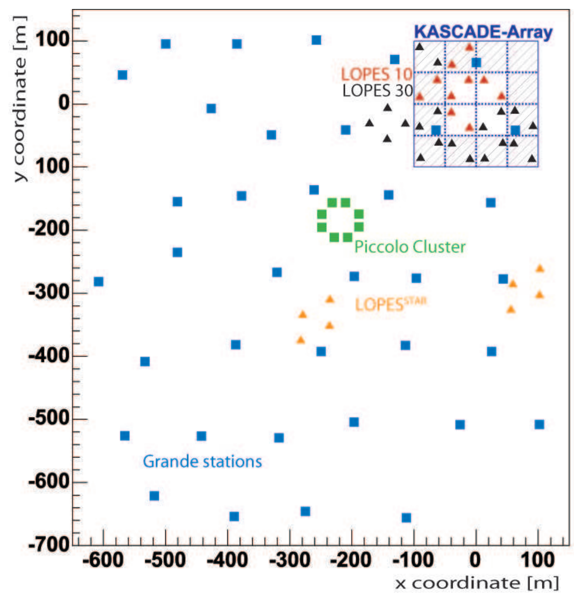

Figure 3. Sketch of the KASCADE-Grande – LOPES experiment: The KASCADE array, the distribution of the 37 stations of the Grande array, and the small Piccolo cluster for fast trigger purposes are shown. The location of the 30 LOPES radio antennas is also displayed as well as the LOPES$^{\mathrm{STAR}}$ antennas.

The KASCADE array measures the total electron and muon numbers ($E_{\mu,\mathrm{kin}} > 230\,\mathrm{MeV}$) of the shower separately using an array of 252 detector stations containing shielded and unshielded detectors at the same place in a grid of $200 \times 200\,\mathrm{m}^2$ (Fig. 2). The excellent time resolution of these detectors allows also decent investigations of the arrival directions of the showers in searching large scale anisotropies and, if existent, cosmic ray point sources. The KASCADE array is optimized to measure EAS in the energy range of 100 TeV to 80 PeV.

A muon tracking detector measures the incidence angles of muons relative to the shower arrival direction. These measurements provide a sensitivity to the longitudinal development of the showers. The hadronic core of the shower is measured by a $300\,\mathrm{m}^2$ iron sampling calorimeter installed at the KASCADE central detector. And three further components offer additional valuable information on the penetrating muonic component at different energy thresholds. The

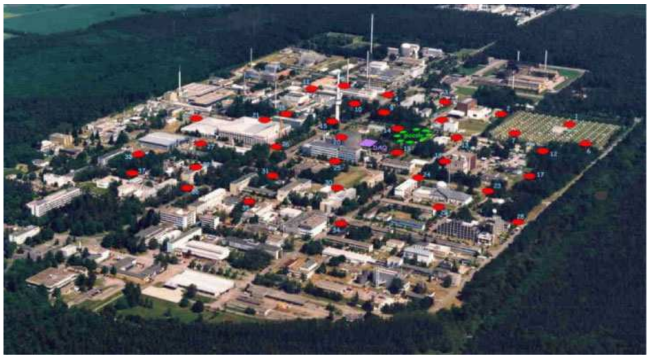

Figure 4. Photograph of the Forschungszentrum Karlsruhe. KASCADE is situated in the North-eastern corner of the center; the Grande stations are indicated by red dots, the Piccolo array by green dots.

Figure 5. Photograph of the experimental set-up in Karlsruhe with several KASCADE array stations. In the foreground a LOPES antenna is seen, in the background a Grande station on top of the underground muon tracking detector.

complementary information of the showers measured by the central and the muon tracking detectors is predominantly being used for a better understanding of the features of an air-shower and for tests and improvements of the hadronic interaction models underlying the analyses [7].

The multi-detector concept of the KASCADE experiment, which is operating since 1996 has been translated to higher primary energies through KASCADE-Grande [8]. The 37 stations of the Grande Array (Fig. 3) extend the cosmic ray measurements up to primary energies of 1 EeV. The Grande stations, 10 m^2 of plastic scintillator detectors each, are spaced at approximative by 130 m covering a total area of ~ 0.5 km^2. In addition, a small cluster of stations (Piccolo) close to the center of the Grande array is installed in order to provide a fast trigger to the muon detection systems of the original KASCADE array.

For the calibration of the radio signal emitted by the air shower in the atmosphere an array of first 10 and meanwhile 30 dipole antennas (LOPES) is set up on site of the KASCADE-Grande experiment [9, 10]. The basic idea of the LOPES (= LOFAR prototype station) project is to build an array of relatively simple, quasi-omnidirectional dipole antennas, where the received waves are digitized and sent to a central computer. This combines the advantages of low-gain antennas, such as the large field of view, with those of high-gain antennas, like the high sensitivity and good background suppression. With LOPES it is possible to store the received data stream for a certain period of time, i.e. at a detection of a transient phenomenom like an air shower retrospectively a beam in the desired direction can be formed. The air shower experiment KASCADE-Grande provides a trigger of high-energy events and additionally with its direction reconstruction a starting point for the radio data analyses and the beam forming. In the current status LOPES operates 30 short dipole radio antennas (LOPES-30) having now an absolute calibration. Data of the first 10 antennas forming LOPES-10 have so far been analyzed. All LOPES-30 antennas are deployed in east-west direction, measuring the east-west polarization, only. In a new measuring campaign, also dual-polarized LOPES antennas will be used. In addition, LOPES runs a field of logarithmic-dipole-antennas (LPDA) which are optimized for an application at the Pierre-Auger-Observatory, and for developing a self-trigger system (LOPES$^{\mathrm{STAR}}$) [11]. The layout is depicted in Fig. 3. All the antennas operate in the frequency range of $40 - 80$ MHz. The read out window for each LOPES-30 antenna is 0.8 ms

wide, the sampling rate is 80 MHz. The geometry of the antenna and the aluminum ground screen give the highest sensitivity to the zenith and half sensitivity to zenith angles of $43° - 65°$, dependent on the azimuth angle. LOPES-30 data are read out if KASCADE-Grande triggers by a high multiplicity of fired stations, corresponding to primary energies above $\approx 10^{16}$ eV. Such showers are detected at a rate of $\approx 2 - 3$ per minute.

3. KASCADE: Light primaries drop a curtsy

'An analysis of these and other data available in the literature indicates that there is, very probably, an irregularity in the shower size distribution curve in the region between 10^6 and 10^7 particles.'
from: On the size spectrum of extensive air showers (1959), G.V. Kulikov and G.B. Khristiansen [1].

The KASCADE data analyses aims to reconstruct the energy spectra of individual mass groups taking into account not only different shower observables, but also their correlation on an event-by-event basis. The content of each cell of the two-dimensional spectrum of reconstructed electron number vs. muon number is the sum of contributions from the individual primary elements. Hence the inverse problem $g(y) = \int K(y,x)p(x)dx$ with $y = (N_e, N_\mu^{\mathrm{tr}})$ (see Fig. 6) and $x = (E, A)$ has to be solved. This problem results in a system of coupled Fredholm integral equations of the form $\frac{dJ}{d \lg N_e \, d \lg N_\mu^{tr}} = \sum_A \int\limits_{-\infty}^{+\infty} \frac{d J_A}{d \lg E} \cdot p_A(\lg N_e \, , \, \lg N_\mu^{tr} \, \mid \lg E) \cdot d \lg E$ where the probability p_A is obtained by Monte Carlo simulations on basis of two different hadronic interaction models (QGSJET 01 [12], SIBYLL 2.1 [13]) as options embedded in CORSIKA [14]. By applying these procedures (with the assumption of five primary mass groups) to the experimental data energy spectra are obtained as displayed in Figs. 7 and 8. The results are also shown in Fig. 1, where the resulting spectra for primary oxygen, silicon, and iron are summed up for a better visibility.

A knee like feature is clearly visible in the all particle spectrum, which is the sum of the unfolded single mass group spectra, as well as in the spectra of primary proton and helium. This demonstrates that the elemental composition of cosmic rays is dominated by the light components below the knee and by a heavy component above the knee feature. Thus, the knee feature originates from a decreasing flux of the light primary particles [15]. Recently, the described analysis was repeated by using a different low energy interaction model (FLUKA [16]) and by comparing the resulting spectra of cosmic rays registered in different ranges of the zenith angle. Fig. 9 displays the results, where it is seen that the above mentioned findings are confirmed [17].

Comparing the unfolding results based on the two different high-energy hadronic interaction models QGSJet and SIBYLL, the model dependence when interpreting the data is obvious. Modeling the hadronic interactions underlies assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by the discrepancies of the results presented here. In Fig. 6 the predictions of the N_e and N_μ^{tr} correlation for the two models are overlayed to the measured distribution in case of proton and iron primaries. It is remarkable that all four lines have a more or less parallel slope which is different from the data distribution. There, the knee is visible as kink to a flatter N_e-N_μ^{tr} dependence above $\lg N_\mu^{tr} \approx 4.2$. Comparing the residuals of the unfolded two dimensional distributions for the different models with the initial data set one can conclude that at lower energies the SIBYLL model and at higher energies the QGSJET model are able to describe the correlation consistently, but none

of the present models gives a contenting description of the whole data set [7].

Crucial parameters in the modeling of hadronic interaction models which can be responsible for these inconsistencies are the total nucleus-air cross-section and the parts of the inelastic and diffractive cross sections leading to shifts of the position of the shower maximum in the atmosphere, and therefore to a change of the muon and electron numbers as well as to their correlation on single air shower basis. The multiplicity of the pion generation at all energies at the hadronic interactions during the air shower development is also a 'semi-free' parameter in the air-shower modeling as accelerator data have still large uncertainties.

Arbitrary changes of free parameters in the interaction models will change the correlation of all shower parameters. Tests using KASCADE observables, which are measured independently of such used in the unfolding procedure, may give further constraints, in particular by investigating correlations of the hadronic shower component with electron or muon numbers. The aim is to provide hints for the model builder groups how the parameters (and the theory) should be modified in order to describe all the data consistently.

The applied method here is to evaluate the measured data relative to simulations (including the detector response) of proton and iron primaries. The measured data points should fall between these extreme values, otherwise the simulations are unable to describe this specific observable correlation. More direct comparisons between data and simulations are not possible due to the unknown composition of the primary particles generating the air showers. This kind of tests is performed for a large set of interaction models available in the simulation package CORSIKA [14]. Results [18, 7] of such detailed investigations confirm the deficiencies of the hadronic interaction models.

In summary, there are still deficiencies of the hadronic interaction models (in particular in describing the high energy interactions) which are revealed by the high accuracy data of KASCADE. But combining all the correlations, the final observables of the showers have not to be different by more than $\approx 15\%$ to be consistent with the data. This requires rather a fine-tuning

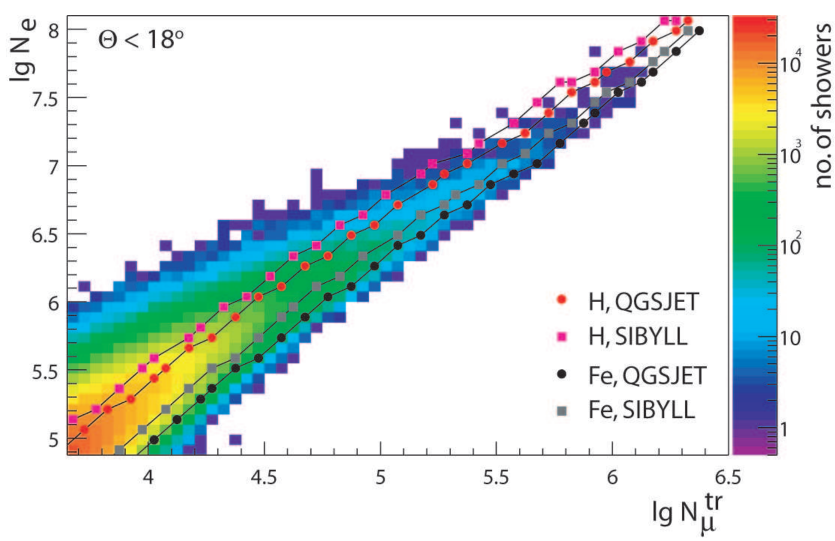

Figure 6. Two dimensional electron (N_e) vs. muon ($N_\mu^{\rm tr}$ =number of muons within 40-200m core distance) number spectrum measured by the KASCADE array. The lines display the most probable values for proton and iron primaries obtained by CORSIKA simulations employing different hadronic interaction models [7].

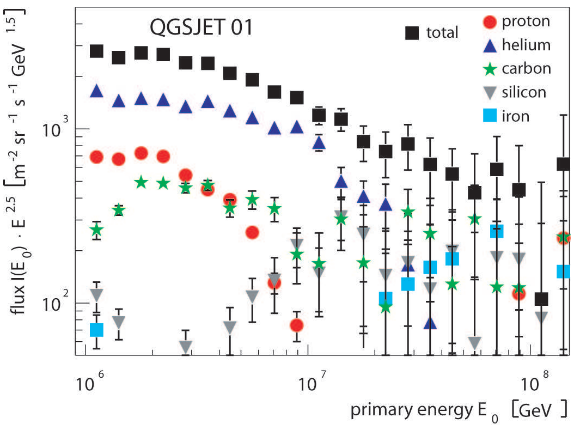

Figure 7. Result of the unfolding procedure based on QGSJET 01 [15].

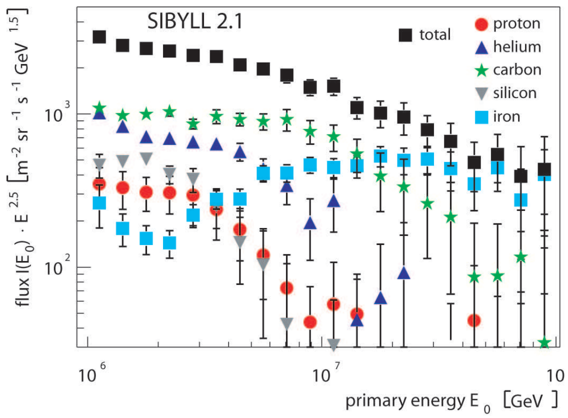

Figure 8. Result of the unfolding procedure based on SIBYLL 2.1 [15].

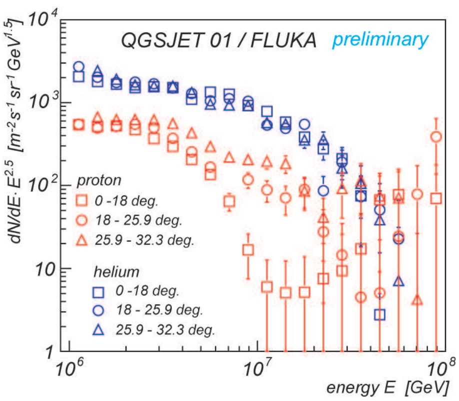

Figure 9. Comparisons of the energy spectra of protons and Helium for different zenith angular ranges [17].

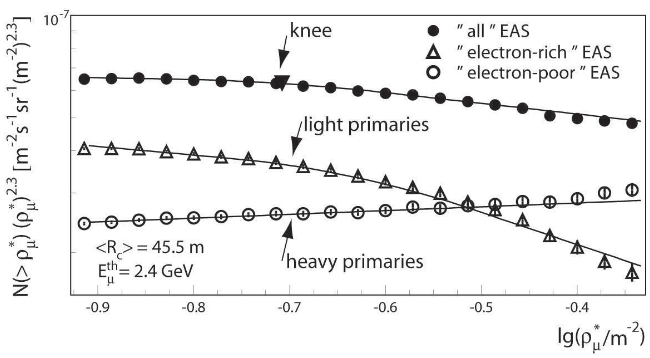

Figure 10. Muon density spectra for different samples of EAS as obtained by KASCADE measurements [19].

of the free parameters in the simulation of the hadronic interactions than a need on new physics.

Neglecting somehow the uncertainties by the interaction models, KASCADE used an additional independent and more direct approach to interprete the measurements (Fig. 10). By using three observables (one observable as energy identifier - the local muon density of high energy muons; and two observables as mass identifier - the ratio of electron to low energy muon number for dividing the whole EAS sample in a sample generated by light primaries and heavy primaries) KASCADE could impressively and in a nearly model independent way demonstrate that the knee is caused by the decreasing flux of light primaries [19].

Investigations of anisotropies in the arrival directions of the cosmic rays give additional information on the cosmic ray origin and of their propagation. Depending on the model of the origin of the knee and on the assumed structure of the galactic magnetic field one expects large-scale anisotropies on a scale of 10^{-4} to 10^{-2} in the energy region of the knee. The limits of large-scale anisotropy analyzing the KASCADE data are determined to be between 10^{-3} at 0.7 PeV primary energy and 10^{-2} at 6 PeV [20]. These limits were obtained by investigations of

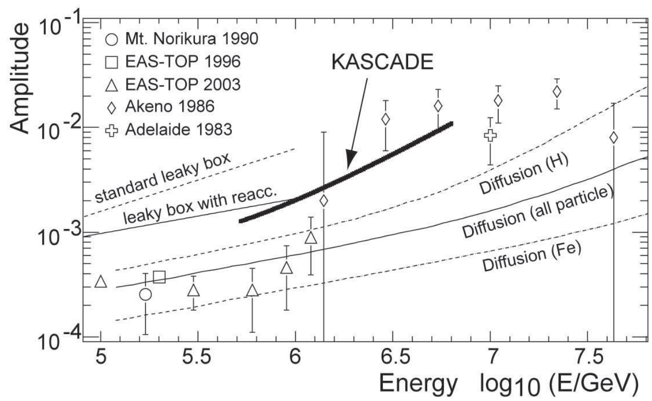

Figure 11. Rayleigh amplitude of the harmonic analyses of the KASCADE data [20] (limit on a 95% confidence level) compared to theory predictions [21].

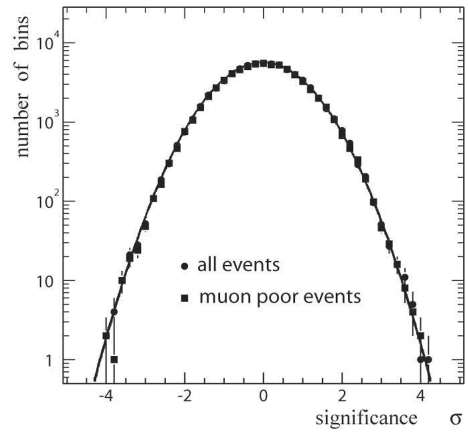

Figure 12. Significance distributions for searching point sources on the sky map seen by the KASCADE experiment [22].

the Rayleigh amplitudes and phases of the first harmonics. Taking into account possible nearby sources of galactic cosmic rays like the Vela Supernova remnant the limits of KASCADE already exclude particular model predictions.

The interest for looking to point sources in the KASCADE data sample arises from the possibility of unknown near-by sources, where the deflection of the charged cosmic rays would be small or by sources emitting neutral particles like high-energy gammas or neutrons. The scenario for neutrons is very interesting for KASCADE-Grande, since the neutron decay length at these energies is in the order of the distance to the Galactic center. In KASCADE case no significant excess was found [22].

4. KASCADE-Grande: Cosmic rays goes metagalactic

'...the observed spectrum is a superposition of the spectra of particles of galactic and metagalactic origin.'
from: On the size spectrum of extensive air showers (1959), G.V. Kulikov and G.B. Khristiansen [1].

The highest energies above the so called ankle at a few EeV are believed to be exclusively of extragalactic origin. Thus, in the experimentally scarcely explored region between the first (proton) knee and the ankle there are two more peculiarities of the cosmic ray spectrum expected: (i) A knee of the heavy component which is either expected (depending on the model) at the position of the first knee scaled with Z (the charge) or alternatively with A (the mass) of iron. (ii) A transition region from galactic to extragalactic origin of cosmic rays, where there is no theoretical reason for a smooth crossover in slope and flux. Dependent on the considered astrophysical model the second knee is allocated to case (i) or (ii), respectively [23].

To distinguish between the two astrophysical scenarios shown in Figure 1 constraints can be given by clarifying the existence and source of the second knee, which is possible by determining the mass composition in the relevant energy range in detail. It is obvious that for the range

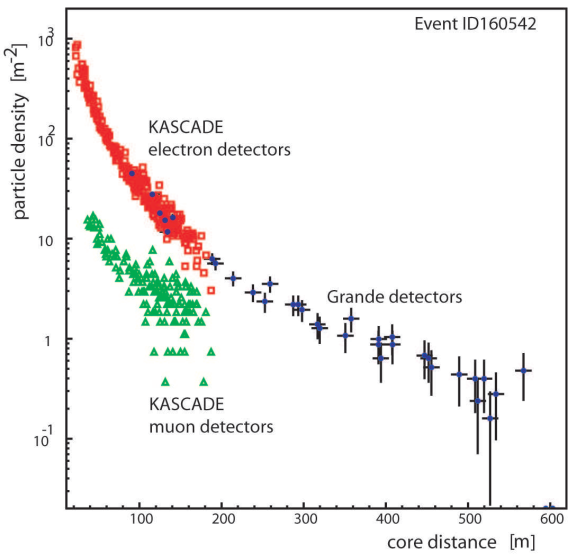

Figure 13. Particle densities in the different detector types of KASCADE-Grande measured for a single event.

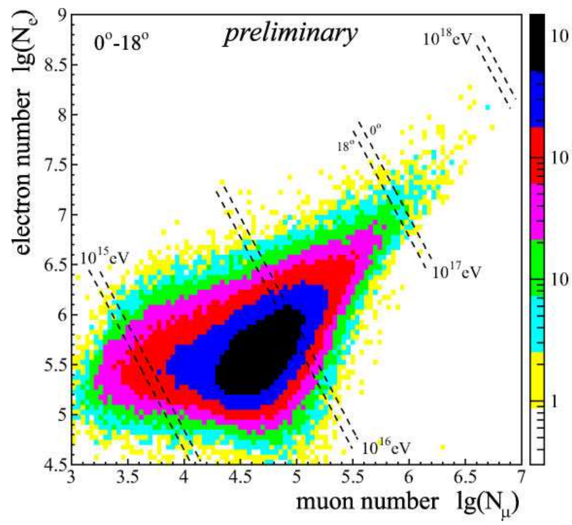

Figure 14. Reconstructed electron vs. muon number size spectrum after one year of data taking of KASCADE-Grande [24].

between 50 and 1000 PeV sophisticated experiments are needed to measure the EAS with the same statistical and reconstruction accuracy as the KASCADE experiment discussed in the previous section.

Fig. 13 shows, for a single shower, the lateral distribution of electrons and muons reconstructed with KASCADE and the charge particle densities measured by the Grande stations. This example illustrates the capabilities of KASCADE-Grande and the high quality of the data. The KASCADE-Grande reconstruction procedure follows iterative steps: shower core position, angle-of-incidence, and total number of charged particles are estimated from Grande array data [24]; the muon densities and the reconstruction of the total muon number are provided by the KASCADE muon detectors [25].

In particular the possibility to reconstruct the total muon number for Grande measured showers is the salient feature of KASCADE-Grande compared to other experiments in this energy range. To describe the lateral distribution (LDF) of the muons a Lagutin-like function is used. In order to obtain stable fit results at single air shower reconstruction, the shape parameter of the Lagutin-LDF is kept constant and only the muon number is estimated.

Figure 15 presents measured and simulated LDFs for different primary energies, where the energy has been roughly estimated by a linear combination of reconstructed total electron and muon numbers [26]. Generally, the agreement between data and MC is very good and the LDF describes the data reasonable well.

At the KASCADE experiment, the two-dimensional distribution shower size - truncated number of muons played the fundamental role in reconstruction of energy spectra of single mass groups. Hence, Figure 14 illustrates the capability of KASCADE-Grande to perform an unfolding procedure like in KASCADE. A hundred percent efficiency for KASCADE-Grande is reached for all primary particle types at energies above $2 \cdot 10^{16}$ eV, thus providing a large overlap with the KASCADE energy range.

KASCADE-Grande started end of 2003 with combined measurements of all detector

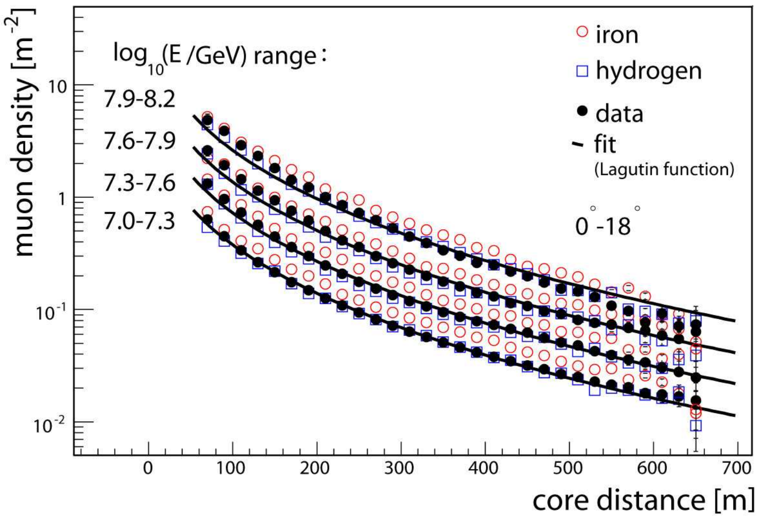

Figure 15. Lateral density distributions of muons measured with KASCADE-Grande compared with simulated distributions [26].

components. Due to the fact that also for KASCADE-Grande a wealth of information on individual showers is available, tests of the hadronic interaction models and anisotropy studies will be possible in addition to the reconstruction of energy spectrum and composition.

5. LOPES: Primed for the spectrum's end

'Finally, we note that the mechanism of radio emission, and especially the polarization, must be known to establish quantitative correlations between the radio emission and other air shower characteristics.'
from: Detection of radio emission from extensive air showers with a system of single half-wave dipoles (1967), S.N. Vernov, G.B. Khristiansen et al. [27].

The traditional method to study extensive air showers (EAS) is to measure the secondary particles with sufficiently large particle detector arrays. In general these measurements provide only information on the actual status of the air shower cascade on the particular observation level. This hampers the determination of the properties of the EAS inducing primary as compared to methods like the observation of Cherenkov and fluorescence light [3]. In order to reduce the statistical and systematic uncertainties of the detection and reconstruction of EAS, especially with respect to the detection of cosmic particles of highest energies, there is a current methodical discussion on new detection techniques. Due to technical restrictions in past times the radio emission accompanying cosmic ray air showers was a somewhat neglected EAS feature. For a review on the early investigations of the radio emission in EAS in the 60ties see [28]. However, the study of this EAS component has experienced a revival by recent activities, in particular by the LOPES project.

The main goal of the investigations in Karlsruhe in the frame of LOPES is the 'calibration' of the shower radio emission in the primary energy range of 10^{16} eV to 10^{18} eV. I.e., to investigate in detail the correlation of the measured field strength with the shower parameters, in particular

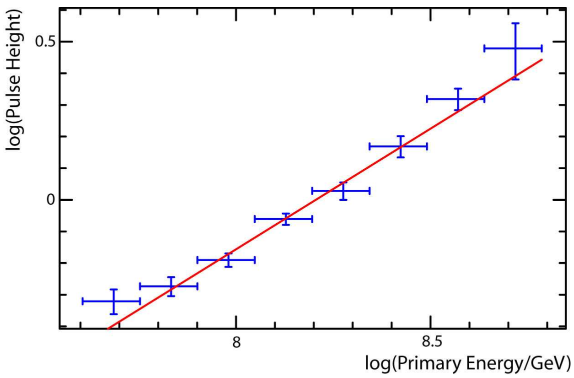

Figure 16. Average radio pulse height of the LOPES-10 detected events (with shower core inside the KASCADE array and corrected for the geomagnetic angle) plotted versus the primary particle energy as reconstructed by KASCADE [32].

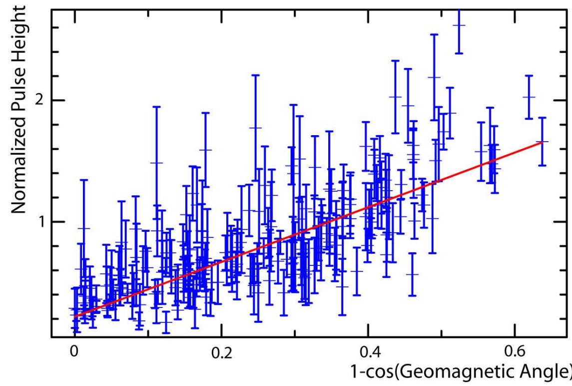

Figure 17. Radio pulse height (corrected for muon number and distance to the shower axis) for individual air showers versus the cosine of the angle to the geomagnetic field. The error bars are the statistical errors [32].

the orientation of the shower axis (geomagnetic angle, azimuth angle, zenith angle), the position of the observer (lateral extension and polarization of the radio signal), and the energy and mass (electron and muon number) of the primary particle. In the following some first results of LOPES will be shown, obtained by a data set with 10 antennas (LOPES-10) installed.

In the frame of LOPES, also theoretical and detailed Monte Carlo studies of the radio emission are performed in the scheme of the so-called coherent geosynchrotron radiation. Here, electron-positron pairs generated in the shower development gyrate in the Earth's magnetic field and emit radio pulses by synchrotron emission [29, 30]. During the shower development the electrons and positrons are concentrated in a thin shower disk ($< 2\,\mathrm{m}$), which is smaller than one wavelength (at $100\,\mathrm{MHz}$) of the emitted radio wave. This situation provides the coherent emission of the radio signal.

When KASCADE-Grande has triggered LOPES the processing of the registered LOPES data includes several steps [32]. First, the relative instrumental delays are corrected using a known TV transmitter visible in the data. Next, the digital filtering, gain corrections and corrections of the trigger delays based on the known shower direction (from KASCADE) are applied and noisy antennas are flagged. Then a time shift of the data and a correction for the azimuth and zenith dependence of the antenna gain is done and the combination of the data is performed calculating the resulting beam from all antennas. This digital beam forming allows to place a narrow antenna beam in the direction of the cosmic ray event. To form the beam the data from each pair of antennas is multiplied time-bin by time-bin, the resulting values are averaged, and then the square root is taken while preserving the sign. The resulting pulse is called the cross-correlation beam or CC-beam. The finally obtained value ϵ_ν, which is the measured amplitude divided by the effective bandwidth, is compared with further shower observables from KASCADE-Grande.

The LOPES-10 data set is subject of various analyses using different selections: With an event sample obtained by stringent cuts the proof of principle to detect air showers in the radio frequency range was given [31].

With showers fallen inside KASCADE the basic correlations with shower parameters are

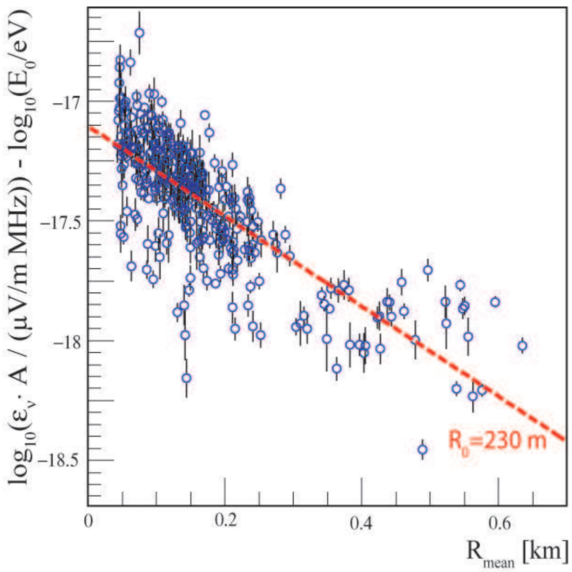

Figure 18. Correlation (sample of distant events) of the pulse height corrected for primary energy with the mean distance of the shower axis to the radio antenna system. The line shows the result of a fit with an exponential function [34].

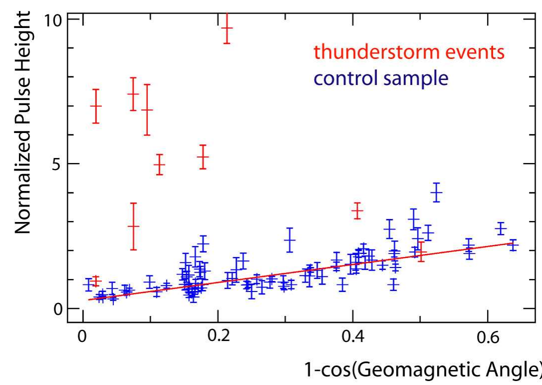

Figure 19. Normalized pulse height of a control sample of detected events and those detected during thunderstorms plotted against the geomagnetic angle. The lines are fits to the data to describe the correlation [33].

shown [6, 32]. As example, Fig 16 depicts the dependence of the reconstructed averaged radio pulse height on the primary energy of the cosmic particles. The shown correlation supports the expectation that the field strength increases by a power-law with an index close to one with the primary energy, i.e. that the received power of the radio signal increases quadratically with the primary energy of the cosmic rays.

Fig. 17 shows the correlation between the normalized reconstructed pulse height of the events with the geomagnetic angle. Normalized here means, that the detected pulse height is corrected for the dependence on the muon number, i.e. to a large extent, the primary energy, and distance to the shower axis. The clear correlation found suggests a geomagnetic origin for the emission mechanism [6].

Besides the analyses of events with the core inside the antenna set-up, KASCADE-Grande gives the possibility to search for distant events. For each (large) shower triggering KASCADE, the information from the extension of KASCADE, i.e. from the Grande array, is available. From that information the shower can be reconstructed even if the core is outside the original KASCADE area, and a radio signal can be searched for events which have distances up to 800 m from the center of the antenna set-up. LOPES-10 detects clear EAS radio events at more than 500 m distance from the shower axis for primary energies below 10^{18} eV. That itself is a remarkable result, but in addition, an important issue is the functional form of the dependence of the radio field strength with distance to the shower axis. After linear scaling of the pulse amplitude with the primary energy estimated by KASCADE-Grande a clear correlation with the mean distance of the shower axis to the antennas is found (Fig. 18). This correlation can be described by an exponential function with a scaling radius in the order of a few hundred meters [34].

Further interesting features are investigated with a sample of very inclined showers [35]. The sample is of special interest for a large scale application of this detection technique, as due to

the low attenuation in the atmosphere also very inclined showers should be detectable with high efficiency. With LOPES one could show that events above 70° zenith angle still emit a detectable radio signal.

Measurements during thunderstorms are of interest to investigate the role of the atmospheric electric field in the emission process. The contribution of an electric field to the emission mechanism is examined both, theoretically and experimentally. Two mechanisms of amplification of radio emission are considered: the acceleration radiation of the shower particles and the radiation from the current that is produced by ionization electrons moving in the electric field. The LOPES data is sampled in events recorded during thunderstorms, periods of heavy cloudiness and periods of cloudless weather. The finding is that during thunderstorms the radio emission can be strongly enhanced (Fig. 19). No amplified pulses were found during periods of cloudless sky or heavy cloudiness, suggesting that the electric field effect for radio air shower measurements can be safely ignored during non-thunderstorm conditions [36].

Meanwhile in LOPES 30 LOFAR-type antennas are in operation (and in addition 11 dual polarized STAR-antennas [11]). LOPES-30 [37] (see Fig.3) has now a maximum baseline of approximately 260 m by the addition of 20 new antennas. Each single antenna is absolute calibrated using a commercial reference antenna. The array provides now a larger sampling area to the radio signal of a single event compared with the original LOPES-10 set-up. This provides the possibility for a more detailed investigation of the radio signal on a single air shower basis, in particular of its lateral extension. In addition, during the LOPES-30 measurements, emphasis is put on monitoring environmental conditions by measuring the static electric field and by recording parameters of nearby weather stations. Atmospheric conditions, in particular E-field variations during thunderstorms, probably influence the radio emission during the shower development, and the measurement of the radio pulses. By monitoring the environmental conditions, and comparing them with the antenna noise level as well as with the detected air shower radio signals, correlations will be investigated and corrected for. Hence, finally the obtained pulse amplitude can be directly compared with theoretical expectations for the radio field strength [30].

6. Conclusions

The KASCADE measurements demonstrate that the knee in the primary cosmic ray spectrum, positioned at few times 10^{15} eV is originating from the depletion of the light elements, and that we should expect consequently further kinks of the spectrum when the heavier elements are disappearing. In any case if this feature is Z- or A-dependent remains a question of great interest.

The measurements give also evidence that cosmic rays of energies around the knee arrive our Earth isotropically. In addition the careful analyses of the KASCADE data on basis of current hadronic interaction models, unavoidably invoked for the interpretation, reveal the deficiencies of the present models. None of them is able to describe the data satisfactorily. The main uncertainties of the KASCADE results arise from such kind a 'model' dependence. It is is also a consequence of the lack of accelerator data at relevant energies, especially in the forward direction, which could help to tune the model descriptions adequately.

Actually, in spite of the success of recent sophisticated experiments like KASCADE, they provide only weak constraints for detailed astrophysical models of origin, acceleration and propagation of cosmic rays for explaining the discontinuities in the primary cosmic ray spectrum.

The extension of KASCADE to KASCADE-Grande aims at the question if there do exist at higher energies knee-like structure associated with the disappearance of the heavier elements.

This feature is expected to constrain more details of the astrophysical models and conjectures. KASCADE-Grande proceeds with the multi detector concept of the measurements in order also to investigate, in particular different aspects of the hadronic interaction models up to primary energies of 10^{18} eV.

With setting up a small array of simple dipole antennas within the area of KASCADE-Grande, using sophisticated electronic and reconstruction procedures, it is attempted to develop a concept of air shower detection by the radio frequency emission during the shower development. First results obtained by correlating of the observed radio field strength with the shower parameters obtained by the KASCADE measurements appear to be very promising for a more detailed understanding of the emission mechanism from atmospheric showers. The main goal of the LOPES project with installing an increased number of antennas is the investigation of the relation between the radio emission from extensive air showers with the properties of the primary particles. Such studies are hoped to pave the way for a large-scale application of a novel technique in future cosmic ray experiments.

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